

Higgs boson searches at LEP

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Abstract. In this paper we report on the legacy of Higgs boson searches at LEP. Specifically, the results of the statistical combination of the searches carried out by the ALEPH, DELPHI, L3 and OPAL experiments are presented. In the search for the Standard Model (SM) Higgs boson, a signal with $m_h < 114.4 \text{ GeV}/c^2$ has been excluded at the 95% confidence level (CL) or higher. The LEP collaborations also carried out extensive searches for Higgs particles predicted by many scenarios beyond the Standard Model. Here we can only report on a very small fraction of these searches and refer the reader to the complete list of LEP-combined search results.

1. Introduction

During the decade when it operated, the Large Electron-Positron (LEP) collider at CERN was at the forefront of the search for evidence of Higgs bosons, which are predicted by the Higgs mechanism to be at the heart of the explanation for the masses of elementary particles. The four LEP experiments carried out extensive searches for the Higgs scalar predicted in the context of the Standard Model (SM). More complex Higgs sectors, such as those predicted by Two Higgs Doublet Models (THDM) or comprising scalars with unusual decay modes (e.g., fermiophobic Higgs, invisible Higgs) were also searched for. In the second phase of LEP (from 1996 onwards, at centre-of-mass energies above the W pair production threshold) the sensitivity to a possible signal was increased by maximizing the integrated luminosity of the collected data samples, as well as the e^+e^- centre-of-mass energy \sqrt{s} , which was increased every year. In the year 2000, its final year of operation, LEP2 delivered data to the experiments at energies up to $\sqrt{s} = 209 \text{ GeV}$. Additional sensitivity to possible signals was obtained by statistically combining the search results of the four individual experiments. The combined LEP2 data sample used by the LEP Higgs working group totalled 2461 pb^{-1} collected between $\sqrt{s} = 189 - 209 \text{ GeV}$ (of which 536 pb^{-1} (32.5 pb^{-1}) were accumulated at $\sqrt{s} \geq 206$ (208) GeV).

2. The search for the SM Higgs boson

At LEP the main process for SM Higgs production is the Higgsstrahlung process, $e^+e^- \rightarrow HZ$, which has a kinematic threshold at $m_H = \sqrt{s} - m_Z$. (Small additional contributions to Higgs production, via WW/ZZ fusion ($e^+e^- \rightarrow \nu_e \bar{\nu}_e H / e^+e^- H$) allow some additional sensitivity beyond this threshold.) The main search topologies are therefore dictated by the dominant Higgs decay modes (mostly $b\bar{b}$, some $\tau^+\tau^-$) and the Z decay modes. All four LEP experiments carried out searches for $(H \rightarrow b\bar{b})(Z \rightarrow \ell^+\ell^-, \nu\bar{\nu}, q\bar{q})$ (respectively: the leptonic¹, missing

¹ Here we use the symbol ℓ and the word “lepton” to denote an electron or a muon.

energy, and four-jet topologies), and for the main topologies with taus: $(H \rightarrow \tau^+\tau^-)(Z \rightarrow q\bar{q})$ and $(H \rightarrow b\bar{b})(Z \rightarrow \tau^+\tau^-)$. Here we report on the LEP-wide combination [1], which is based on the final results of the Higgs search by the individual collaborations [2, 3, 4, 5].

The search backgrounds were reduced by applying suitable event selection criteria including, crucially for most search channels, the ability to experimentally tag b-jets. Typically, after selection the remaining background consisted mostly of ZZ and W^+W^- events (including small contributions from Ze^+e^- , $Z\nu\bar{\nu}$, $W^\pm e\nu$) and $q\bar{q}$ events with additional gluon radiation.

The combination of the results of the four experiments is based on the ratio of the extended likelihoods for the signal-plus-background hypothesis and the background-only hypothesis (full details available in Ref. [1]):

$$Q = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b}, \quad -2 \ln Q(m_h) = 2s_{\text{tot}}(m_h) - 2 \sum_i \ln(1 + (\frac{s(m_h)}{b})_i) \quad (1)$$

where s_{tot} is the total expected signal in a given search channel (i.e., for a given centre-of-mass energy, search topology, experiment) and the sum is over all the candidate events selected in the data sample. Each candidate event i selected in the data contributes a weight $\ln(1 + s/b)$ to the test statistic $-2 \ln Q$, where s and b are the signal and background expected in the bin of some discriminating variable where the candidate lies. (1D and 2D discriminants based on e.g., reconstructed Higgs mass, b-tagging probability, neural network output, were used.) Independent search channels are combined by adding the respective $-2 \ln Q$ contributions. In order to determine robustly how background-like or signal-plus-background-like an observed result is, it is compared with the outcome of a large number of toy MC experiments. Statistical and systematic uncertainties are included in the combination process, and have been verified to have a small effect in the results.

No single LEP experiment has the power to distinguish between the two hypotheses at more than the two-sigma level, for an SM Higgs signal with mass larger than $\sim 114 \text{ GeV}/c^2$. Most of the discriminating power is concentrated in the combined four-jet channels, whose discriminating power roughly equals that of all the other channels put together. For a test mass $m_h = 115 \text{ GeV}/c^2$ the highest weight candidate events observed in the data [1] are three four-jet candidates recorded by ALEPH, and one missing energy candidate recorded by L3. At this test mass, the ALEPH result [2] corresponds to a 3 sigma excess; the L3 result [4], while consistent with the background hypothesis, very slightly favours the signal-plus-background hypothesis; the results of DELPHI [3] and OPAL [5] are consistent with the background-only hypothesis. The combined LEP result at $m_h = 115 \text{ GeV}/c^2$ is in excess of the background-only hypothesis by 1.7 standard deviations. The lower bound on the SM Higgs boson mass at the 95% CL determined from the LEP-combined result is $m_h = 114.4 \text{ GeV}/c^2$, while the median expected limit is $115.3 \text{ GeV}/c^2$. SM Higgs boson signals of lower mass are excluded at higher confidence levels. 95% CL upper bounds on the hZZ coupling in non-standard models were also obtained, from the LEP1 and LEP2 Higgs searches (Fig. 1).

3. The search for Higgs bosons beyond the SM

The Higgs sector of the Minimal Supersymmetric extension to the SM (MSSM) predicts 3 neutral (h , A , H ; $m_h < m_H$) and 2 charged (H^\pm) scalars. The lightest CP-even Higgs boson, whose mass is predicted to be less than $\sim 140 \text{ GeV}/c^2$, can be produced by Higgsstrahlung; a complementary production process is pair production in association with the CP-odd A ($e^+e^- \rightarrow hA$). The final results of the extensive searches for the neutral MSSM Higgs bosons at LEP are reported in detail in Ref. [6] for a number of benchmark scenarios, including CP-conserving/CP-violating Higgs sectors. For instance, in the CP-conserving m_h -max benchmark the following are excluded at the 95% CL or higher: $m_h < 92.9 \text{ GeV}/c^2$, $m_A < 93.4 \text{ GeV}/c^2$, and $0.9 (0.6) < \tan \beta < 1.5 (2.6)$

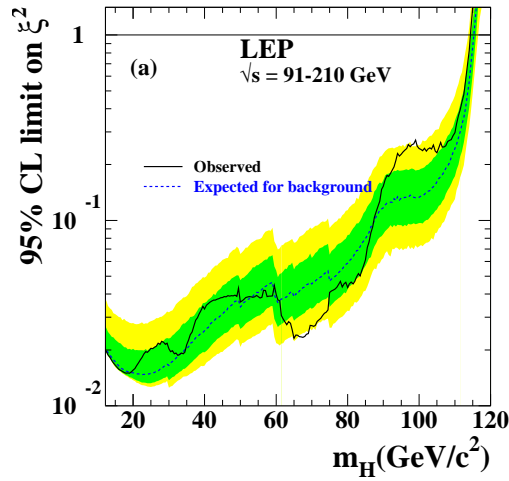


Figure 1. 95% CL limit on the hZZ coupling in non-standard models. $\xi^2 = (g_{hZZ}/g_{hZZ}^{\text{SM}})^2$, where g_{hZZ} is the non-standard hZZ coupling and g_{hZZ}^{SM} is the same coupling in the SM. The Higgs boson is assumed to decay exactly as in the SM, but the production cross-sections for the Higgsstrahlung and fusion processes are scaled with g_{hZZ}^2 [1].

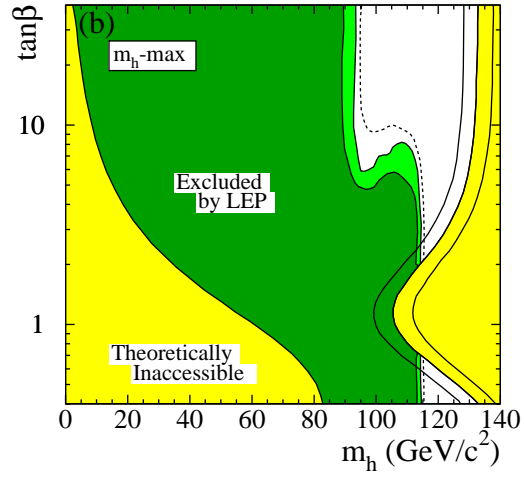


Figure 2. Exclusions at the 95% CL (light green) and 99.7% CL (dark green) in the $(m_h, \tan \beta)$ plane [6] for $m_t = 174.3 \text{ GeV}/c^2$. The dashed line is the expected 95% CL exclusion. Theoretically inaccessible regions are shown in yellow. The parameter space upper boundary on m_h is drawn for (from left to right) $m_t = 169.3, 174.3, 179.3 \text{ GeV}/c^2$.

for $m_t = 179.3 (169.3) \text{ GeV}/c^2$ (Fig. 2)². In the case of CP-violating scenarios the Higgs mass limits can be severely weakened, especially for $\tan \beta \gtrsim 3$.

The results of the searches for pair-produced charged Higgs bosons are reported in [7]: $m_{H^\pm} < 78.6 \text{ GeV}/c^2$ is excluded by the data, at the 95% CL. Finally, searches for neutral Higgs particles with non-standard decay modes were also performed, and strong 95% CL lower bounds were set on the Higgs mass; details can be found elsewhere: Higgs decaying exclusively to $b\bar{b}$ or to $\tau^+\tau^-$ [1], fermiophobic Higgs [8], invisible Higgs [9] and flavour-independent Higgs decays [10].

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² $\tan \beta$ is the ratio of the vacuum expectation values of the two Higgs doublets.